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Agricultural Memorandum No. 580. -I

On the movement of water from the soil
- a synopsis and commentary on some field data.

C V Smith

Introduction

Working solutions to the problems posed by the extraction and restoration of soil moisture reserves enable comment on irrigation need, on the time available for field drainage works, and on field cultivations of all kinds. Any study of the response of field crops to weather must include some comment on the magnitude of the soil moisture stress, and offer some indication of the root zone that exhibits a soil moisture deficit. There are also applications to the problems of hydrology as distinct from agriculture.

One reason for taking up the discussion at this time is the recent publication of the results of 10 years experimentation at Rothamsted (Rothamsted Experimental Station - Report for 1972).

I Bare Soil

1. The basic data provided by Rothamsted are shown in Table 1 (III), where their table numbering is retained.

Table 1 (III)

Bare Soil, 1962, 1963. Water balance (mm)

	Period	R	D	R + D	d	R+D-d	ΣE_T
	1962						
1	22/5-28/5	5	8	13	1	12	12
2	28/5-4/6	1	12	13	0	13	27
3	4/6-25/6	4	18	22	-	22	89
4	25/6-29/6	3	-2	1	-	1	100
5	29/6-2/7	0	1	1	-	1	107
6	2/7-13/7	6	2	8	-	8	132
7	13/7-23/7	21	-6	15	-	15	155
8	23/7-31/7	36	-10	26	16	10	170
9	31/7-8/8	23	-12	11	7	4	189
10	8/8-22/8	33	3	36	11	25	215
11	22/8-13/9	46	-6	40	10	30	251
	1963						
1	7/6-12/6	47	-18	29	22	7	14
2	12/6-19/6	12	1	13	0	13	31
3	19/6-24/6	3	2	5	-	5	45
4	24/6-17/7	68	-6	62	25	37	94
5	17/7-2/8	2	29	31	0	31	134
6	2/8-13/8	19	-4	15	0	15	160
7	13/8-3/9	76	-36	40	24	16	191
8	3/9-12/9	19	14	33	6	27	208
9	12/9-7/11	80	-22	59	28	31	253

Where R = rainfall
D = soil drying
d = drainage through soil depth being studied
E = R-d+D = soil moisture loss due to evaporation or transpiration
E_T = potential transpiration of a short, green, well watered crop.

It is of interest to include the implied information on E_T over each period of observation and D the summation of the soil drying (from a zero value at the time of the first observation). These data are shown in Table 1 (III) A.

Table 1 (III) A

	Period 1962	R	D	Σ D	d	ΣE_T	E_T	E=R-d+D
1	22/5-28/5	5	8	8	1	12	12	12
2	28/5-4/6	1	12	20	0	27	15	13
3	4/6-25/6	4	18	38	-	89	62	22
4	25/6-29/6	3	-2	36	-	100	11	1
5	29/6-2/7	0	1	37	-	107	7	1
6	2/7-13/7	6	2	39	-	132	25	8
7	13/7-23/7	21	-6	33	-	155	23	15
8	23/7-31/7	36	-10	23	16	170	15	10
9	31/7-8/8	23	-12	11	7	189	19	4
10	8/8-22/8	33	3	14	11	215	26	25
11	22/8-13/9	46	-6	8	10	251	36	30
	1963							
1	7/6-12/6	47	-18	-18	22	14	14	7
2	12/6-19/6	12	1	-17	0	31	17	13
3	19/6-24/6	3	2	-15	-	45	14	5
4	24/6-17/7	68	-6	-21	25	94	49	37
5	17/7-2/8	2	29	8	0	134	40	31
6	2/8-13/8	19	-4	4	0	160	26	15
7	13/8-3/9	76	-36	-32	24	191	31	16
8	3/9-12/9	19	14	-18	6	208	17	27
9	12/9-7/11	80	-22	- 4	28	253	47	30

2. As advisers, our interest is in generalised models of water extraction from the soil. It is possibly significant, and indicative of the difficulties of interpretation of the field data, that the Rothamsted Report does not attempt to do this explicitly, but simply contents itself with the presentation of results. In the strict scientific sense this is possibly the wiser course of action.

One is aware of the dangers of placing greater weight on results than the original investigators are prepared to do; under the pressure of requirements for working solutions, there is but little alternative to attempt some generalisation of the relationships between E, E_T and R, D and d. The justifications for such a step must include an awareness of the possible errors of measurement, appeals to physical reasoning and appeals to reasonable assumptions.

The first part of the Rothamsted Report is devoted to a study of the accuracy of the neutron probe and of the direct measurement of D, the change in soil moisture content, under a variety of crops. There are obviously many potential sources of error. These include the representativeness of the sampling site, and the implied, occasional exterior flooding of the neutron probe access tube, due to poor soil contact.

Before attempting a model of behaviour for the Rothamsted soil type, some smoothing of the data is undertaken.

3. 1962. Period 4

Rainfall of 3mm apparently produced a soil wetting of 2mm ($D = -2$mm). This is not consistent with other measurements of D over periods 1 to 6, where R is small and $E_T > R$. Despite the general observation that rainfall may penetrate the soil profile without bringing any wetted layer back to field capacity, it is suggested now that the inconsistency may be resolved by assuming D of period 3 to be an over-estimate of drying, and returning a net drying over periods 3 and 4 of 16 mm.

Periods 5 and 6

It is suggested that the measured, small values of D under conditions of high soil moisture deficit ($\Sigma D > 35$mm) are within the limits of error of measurement, and are not significant.

Period 10

The reported drying of the soil ($D = 3$mm) under a re-wetting phase is inconsistent with the general run of observations over periods 7 to 11, where R is large and generally greater than E_T. On the assumption that this apparent drying is brought about by an over-estimate of the wetting in period 9 ($D = -12$mm), by requiring the same net value of D over periods 9 and 10, and by requiring that D of period 10 should be of negative sign (some wetting), we obtain the figures shown in Table 1 (III) B.

Table 1 (III) B

Period 1962	R	D	ΣD	d	E_T	E	E/E_T
1	5	8	8	1	12	12	1.00
2	1	12	20	0	15	13	1.15
3	4	16	36	–	62	20	0.32
4	3	0	36	–	11	3	0.27
5	0	1	37	–	7	1	.14
6	6	2	39	–	25	8	.24
7	21	–6	33	–	23	15	.65
8	36	–10	23	16	15	10	.66
9	23	– 8	15	7	19	8	.42
10	33	– 1	14	11	26	22	.85
11	46	– 6	8	10	36	30	.83
1963							
1 *	47	–16	12	22	14	9	0.64
2	12	– 1	11	0	17	11	0.65
3	3	2	13	0	14	5	0.39
4	68	– 6	7	25	49	37	0.75
5	2	29	36	0	40	31	0.77
6	19	– 4	32	0	26	15	0.57
7 *	76	–21	11	24	31	31	1.00
8	19	– 1	12	6	17	12	0.70
9 *	80	–22	0	28	47	30	0.64

* Possible periods of over-estimate of soil moisture content according to Rothamsted.

4. One set of inferences that may be drawn from the data of Table 1 (III) B, for 1962 is that

(i) The values of E and E_T for each period require that for the Rothamsted soil (clay with flints), the drying phase and the wetting phase need to be treated differently. This hysteresis effect could be due to a shrinking and cracking of the soil on drying, and a swelling (which eventually removes fissures in depth) on wetting.

(ii) The Rothamsted comment that at the time of the first measurement in period 1, the soil was a little above field capacity enables ΣD to be interpreted directly as the soil moisture deficit in the surface layers of the 90 cm profile examined.

A check to evaporation occurs certainly by the time $\Sigma D \simeq 35$mm, and possibly by the time $\Sigma D \simeq 20$mm.

(iii) Over the drying phase, $E \simeq E_T$ until $\Sigma E \simeq 25$mm. If small amounts of rainfall on the surface layers after this time are removed at a rate $E \simeq E_T$, then the depletion of soil moisture reserves proceeds at a mean rate of $E \simeq 0.5E_T$, until $\Sigma D \simeq 35$mm. A further tapering off of the rate of soil drying occurs after this deficit is achieved. Beyond $\Sigma D \simeq 35$mm, $E \simeq$ nominal $0.1\ E_T$.

(iv) Over the re-wetting phase, as a broad approximation.

$$E \simeq 65\%\ E_T$$

$$d \simeq 65\%\ (R-E) \qquad /\text{given } R-E > 0/$$

$$\text{and} \quad D = E - R + d.$$

5. The smoothed data for 1963, Table 1 (III) B are now examined for agreement with these suggestions.

To arrive at the data of Table 1 (III)B from Table 1 (III)A, the starting point is taken to be period 5. For 1963, D now represents the absolute soil moisture deficit.

1963 Period 5

The large value of D, ($D = 29$mm) is taken to be real. With E and E_T both large and greater than D, a final value of D (the absolute soil moisture deficit) at the end of the period is calculated to be 36mm, if the requirements of 4 (iii) are met.

Period 1.

This is noted by Rothamsted as a time when there was possibly some flooding of the gap outside the probe access tube, with some consequent over-estimate of the extent of rewetting of the soil

Taking $E = 65\%\ E_T$, we obtain in period 1, $E = 9$mm and by appropriate adjustment, $D = -16$.

The value of d obtained from the expression $d = 65\% (R-E)$ is 25mm, compared with the observed drainage on a nearby site of 50 cm depth of 22mm.

Period 2

If a net drying $D = -17$ mm is maintained over periods 1 and 2, the value of $D = -1$mm for period 2 results. This in turn implies a value of E, in period 2 of 11mm. This, one may note with some satisfaction is some 65% of E_T (17mm) over the period.

With $R \simeq E$, the implied drainage from our expression for d is zero, as observed.

Period 3

During this period there is a transition from the soil wetting of the previous period to the soil drying demonstrated by the field measurement. Nevertheless, the observed value of E = 5mm is obviously below that suggested in this note as appropriate to the drying phase (when $E \simeq E_T$) or the re-wetting phase (when $E \simeq 65\% \ E_T$).

An alternative consideration is that over the 6 day interval of period 3, the value of E_T = 14mm could be an over-estimate.

At no stage in the report is the procedure used to estimate E_T indicated. With a more detailed analysis of some data given elsewhere in the Rothamsted Report (Table 5 (I) - sugar beet) it is possible to obtain estimates of the ratio E_I/E_T over periods of approximately 1 week. These are shown in Table 5 (I) A below. E_I indicates the evaporation from an irrigated crop.

Table 5(I)A. Water balance (mm) - sugar beet. 1970

Period	ΣE_I	E_I	ΣE_T	E_T	E_I/E_T	Mean E_I/E_T over 2 periods
1	20	20	39	39	0.51	
2	52	32	62	23	1.39)	1.27
3	75	23	82	20	1.15)	
4	93	18	94	12	1.50)	1.27
5	112	19	112	18	1.05)	
6	139	27	129	17	1.59)	1.48
7	161	22	145	16	1.37)	
8	174	13	159	14	0.93)	1.26
9	201	27	176	17	1.59)	
10	222	21	190	14	1.50)	1.21
11	245	23	216	26	0.88)	
12	274	29	228	12	2.42)	1.74
13	291	17	243	15	1.13)	
14	306	15	259	16	0.94)	1.33
15	318	12	266	7	1.71)	
16	345	27	279	13	2.08	

The gross swings in the estimate of E_I/E_T from week to week may be attributed either to variations in estimates of E_I or E_T. On the assumption that after a given growth stage, crop behaviour is reasonably consistent from week to week, and with E_I being measured (though by a difference method it is true) whilst E_T is presumably calculated, one could perhaps assign the swing in E_I/E_T to the value of E_T determined over short periods. Certainly, estimates of E_I/E_T over 2 weekly periods give a more consistent pattern than those over periods of 1 week.

Returning now to the bare soil problem, and to the data of Tables 1 (III) A and B, we may comment that the ratio E/E_T for the combined periods 3 and 4 is 67%. The expected drainage, on the basis of $d \simeq 65\% \, (R-E)$ is 20mm, against the observed value nearby of 25mm.

Period 6

The reported ratio $E/E_T \;=\; 57\%$

Periods 7 and 8

The Rothamsted comment of possible external flooding of the access tube and an over-estimate of the extent of rewetting in period 7, together with a suggested drying in period 8 [Table I (III) A], this during a generally rainy and rewetting phase over periods 6 to 9, calls for some reassessment of all factors. Period 8, Table 1(III) A also presents us with the only period during which $E > E_T$.

A requirement that D should be negative (or zero) in period 8, whilst retaining the same net drying ($D = -22$m) over periods 7 and 8, leads to the figures shown in Table 1 (III) B, if one places the additional contraint that E should not exceed E_T in period 7.

Period 9

This is also indicated by Rothamsted as an interval with possible exterior flooding of the access tube. Nevertheless, on their figures for this period $E \simeq 65\% \, E_T$.

5.1 For all rewetting periods of the wet season of 1963, except that of period 7, which must remain suspect, the relationship

$$E \simeq 65\% \; E_T$$

appears to afford a reasonable working solution. A reasonable guide to the drainage would appear to be met by the relationship

$$d \simeq 65\% \, (R-E)$$

6. The transfer to other soil types, and to other drying and rewetting situations, is not easily made on the basis of the limited evidence of 2 seasons results on a clay (with flints) soil.

Some working solutions of increasing sophistication are now put forward.

6.1 The general evidence of the Rothamsted Report (1972) is that almost any annual crop may extract 55-65mm of water from reserves in the top 30cm of soil at Rothamsted, given the soil is initially at field capacity.

The loss of water by evaporation within a given depth of soil is not necessarily to be equated with that that would be extracted by a foraging plant root system, within the same soil depth.

Nevertheless, if this naive assumption is made, then the evaporative soil moisture loss that may be sustained before a check to evaporation occurs (at a soil moisture deficit of 20-25mm), is equivalent to the water readily available to plants in the top 10-12 cm of a heavy soil.

Whilst it is not suggested that such an equivalence may be used to established anything more than orders of magnitude, we may note that for a light soil type (initially at field capacity) the water in the top 30 cm readily available to plants might be of the order 25-35mm. A check to the evaporative loss from such a bare soil might be expected to occur when either

(a) the readily available water in the top 10-12cm of soil is exhausted ie. at a soil moisture deficit of 10-12mm.

(b) at a soil moisture deficit of 20-25mm, on the assumption that the effect of increasing soil depth (path length) in increasing the total soil resistance to diffusion of vapour through it, is compensated in some degree by the greater porosity of the lighter soil.

The evidence of Penman (1940) is that the diffusion coefficient of water vapour moving through the soil is directly proportional to the (air) porosity of the medium. With the range of porosity in typical agricultural soils covered by a factor of 2 to 3 times the minimum value in heavy soils, then the weight of argument would appear to favour the alternative (b). In this case a check to evaporation might be expected to occur with a soil moisture deficit of 20-25mm in most soils (remembering of course that we are dealing here with the top 30 cm layer, and drying from the surface down).

Earlier evidence from Penman (1941), on a soil type not specified (though the experiment was carried out on the drain gauge at Rothamsted) is that a soil moisture deficit of 0.7 inches (18mm) could be sustained from bare soil, after which a rapid decrease in evaporative loss set in.

In the initial drying phase of bare soil, $E \simeq E_T$ is taken to be broadly valid for all soil types, (though this rate is smaller than that which would occur from an open water surface to which wet bare soil has been equated elsewhere).

The evaporative water loss during the rewetting phase for soils other than clays ie in the absence of imbition and soil cracks, should presumably approach that of the initial drying phase. By the same token, the development of a more uniform wet zone and advancing wetting front in soils other than clays might imply that less weight should be given to through drainage through large fissures. In other words, whilst in the case of clays it is apparently necessary to estimate through-drainage in the rewetting phase before arriving at D, the soil moisture change and water retention, for other soil types, surface and capillary forces within the soil may contain the downward flux of water and we may return to the simpler relationships expressed by

$$E \text{ tends to } E_T$$

$$D = E - R + d$$

avoiding the additional intermediate constraint

$$d \simeq 65\% \, (R - E)$$

6.2 Elementary drying theory postulates 3 distinct phases in the drying process, under constant drying conditions; that is when the temperature and moisture content of the drying air (in this case at the ground) remain constant. Such constant drying conditions of course will never occur in practice, but such a state offers a useful basis for discussion.

In the first phase, when the surface of the drying material remains completely wet, evaporation is similar to that from a free liquid surface of constant area and the drying rate is constant under these stable drying conditions. If we recognise that the term "surface" here implies the matrix surface of the soil in depth, and not simply the ground surface, then this phase describes the behaviour of soil drying, over the period when $E \simeq E_T$ and up to the stage when $D \simeq$ 20-25 mm.

In the second phase of drying, there is a decrease in the surface area that remains wetted, and the drying rate decreases, being directly proportional to the fraction of surface that remains wet. This phase it is suggested corresponds to the situation where

$$35 - 40\text{mm} > D > 20\text{-}25\text{mm}$$

In the third phase, the matrix surface is completely dru; the drying rate again decreases, and is controlled now by the rate at which water can be transferred from the interior of the material to the matrix surface.

Obviously in the case of soil drying, where we do not have a bulk flow of air through the medium being dried, all 3 phases of drying are controlled by diffusion; the first 2 phases by diffusion through the soil and across the surface boundary layer - in the third phase, there is the additional complication of diffusion of water vapour through the soil particles.

If we consider unit cross section of the ground and diffusion of water vapour across the ground surface boundary layer (of depth l) under steady state conditions, we may write

$$q = D_0 \left[\frac{\rho_1 - \rho_2}{l} \right] \text{g/sec}$$

where q is the flux of water vapour through the air of boundary layer (which is taken to be free of any convectional motion)

D_0 is the molecular diffusion coefficient of water vapour through air

ρ_1, ρ_2 are the vapour pressure concentrations on either side of the boundary layer

Typical values for D_0 are of the order 0.24 at temperature levels of interest. From Avogradros Law we may write

$$q = .24 \left[\frac{p_1 - p_2}{l} \right] \frac{18}{22414 \times 1013} \text{g/sec}$$

where p_1, p_2 are now the water vapour pressures (in mb) on either side of the boundary layer.

Mean daily evaporation rates will be given by

$$q = .24 \left[\frac{p_1 - p_2}{l}\right] \frac{18}{22414 \times 1013} \times 60 \times 60 \times 24 \quad \text{g/day}$$

or $$q = .24 \left[\frac{p_1 - p_2}{l}\right] \frac{18 \times 60 \times 60 \times 24 \times 10}{22414 \times 1013} \quad \text{mm water/day}$$

$$q = .164 \left[\frac{p_1 - p_2}{l}\right] \text{mm water/day}$$

With a typical value of $l = .25$ cm
and a mean daily value of $(p_1 - p_2) = 6$mb.,

a numerical value of q is 3.95 mm/day. Such a figure is consistent with observed orders of magnitude of E_T in the summer months.

Other general information in the Rothamsted Report is that with a bare soil, the evaporation falls off rapidly, within a period of a few days, in the second drying phase ($E < E_T$). If we take this period to be 5 days, and indicate an exponential drying rate for the soil over phase 2, then a mean rate of drying over this period is given by

$$\frac{10\text{mm}}{5 \text{ days}} = 0.5\, E_T = 1/5 \int_1^5 E_T e^{-kt} \, . \, dt \quad \text{mm/day}$$

where t is the time in days
k is a constant

A numerical solution indicates $k = 0.148$

The introduction of soil type is effected by the additional resistance to the movement of water vapour through the soil, over the period of soil drying from 25 mm to 35 mm deficit. This resistance must show an exponential increase with soil depth.

A general expression for soil drying, during phase 2 will now be given by

$$q = E_T e^{-.148t} = \frac{.164\,(p_1 - p_2)}{1 + \frac{ae^{Kx}}{\varepsilon}} \quad \text{mm water/day}$$

where a, K are constants
ε is the soil porosity
x is soil distance (in cm) from the
soil surface (ground level)

With 2mm of water available per cm of soil depth, the "dry" zone in the soil increases from 12.5 cm to 17.5 cm over the period of phase 2.
The numberical values obtained when

$$t = 1 \quad \text{and } x = 12.5 \text{ cm}$$

$$t = 5 \quad x = 17.5 \text{ cm}$$

and a typical value of $\epsilon = 0.1$ is assumed for a heavy soil are

$$a = .00003$$

$$K = .39$$

For this, values for $(p_1 - p_2)$ and l are again taken to be 6 mb and .25 cm.

The general expression, during phase , for the rate of water loss from the soil is thus

$$q = \frac{.164\,(p_1 - p_2)}{1 + \frac{.00003\,e^{.39x}}{\epsilon}} \quad \text{mm water/day}$$

Such an expression fits the observed drying in Table 1 (III)B, 1962 period 3; 1963 period 5, for example (given any rain is lost from the layer at a rate $E = E_T$)

If for medium and light soils, water available for evaporation is taken to be 1.5 mm and 1.0 mm respectively per cm of soil depth, whilst the porosities are taken to be 0.2 and 0.3, then substitution in the above general expression indicates the rate of water loss in phase 2, to be as follows

$$E = E_T e^{-.148\,t} \qquad \text{for heavy soils}$$

$$E = E_T e^{-.340\,t} \qquad \text{for medium soils}$$

$$E = E_T e^{-2.06t} \qquad \text{for light soils}$$

The corresponding loss on the first day of phase 2 are

$E = .862\ E_T$ heavy soil
$E = .712\ E_T$ medium soil
$E = .127\ E_T$ light soil

The average loss over phase 2 is

$0.5\ E_T$ for the heavy soil over a 5 day period

$0.3\ E_T$ for the medium soil over a 7 day period

$0.13\ E_T$ for the light soil over a 1 day period

At the end of these times evaporation proceeds at a nominal $0.1\ E_T$. Such calculations also indicate different final, permissible values for $\sum D$ in the 3 soil types.

General models of soil behaviour emerge as follows

Heavy soil

(i) Drying phase ie $D \geqslant o$; $E \geqslant R$

$E = E_T$ until $\sum D = 25$ mm (layer 1)

$E = 0.5\ E_T$ when $35\text{mm} > \sum D > 25\text{mm}$ (layer 2)

$E = 0.1\ E_T$ after $\sum D \geqslant 35$ mm (layer 3)

An upper limit to $\sum D$ is placed at 40mm.

During the drying phase, rainfall is removed at a rate $E = E_T$, and preferentially, before further soil moisture reserves are taken out. In other words, rainfall cancels out soil moisture deficits from the first soil layer downwards; the removal and exhaustion of soil moisture reserves is always in the sequence from layer 1 before layer 2; from layer 2 before layer 3.

(ii) Wetting phase ie $D < o$; $R > E$

$E = 0.65\ E_T$

$d = 0.65\ (R-E)$

$D = E-R+d$

As in the drying phase, rainfall is removed at a rate $E = E_T$ and preferentially, before excess rainfall acts to remove soil moisture deficits from the first layer, downwards. The soil moisture deficit in layer 1 is required to be cancelled before that in layer 2; that of layer 2 is required to be cancelled before that layer 3 is acted on.

Medium Soil

$E = E_T$ until $\sum D = 25\text{mm}$ (layer 1)

$E = 0.3E_T$ when $33\text{mm} > \sum D > 25\text{mm}$ (layer 2)

$E = 0.1E_T$ after $\sum D \geqslant 33\text{mm}$ (layer)

An upper limit to D is placed at 35mm.

As in the case of heavy soil, current rainfall in the period under consideration is removed preferentially, at a rate $E = E_T$.

Soil moisture reserves and soil moisture deficits must be fully removed from the first layer, before those in the second, and subsequently the third layer are acted on.

Light soil

$E = E_T$ until Σ D = 25mm

$E = 0.1E_T$ when Σ D = 25mm

An upper limit to Σ D is placed at 26mm.

Current rainfall in the period under consideration is removed preferentially, at a rate $E = E_T$.

Soil moisture reserves and soil moisture deficits must be fully removed from the first layer before those in the second layer are acted on.

6.3 Any discussion based on a steady state diffusion of water vapour from the soil to the atmosphere ignores the diurnal variation in most of the parameters either directly or indirectly involved. The diurnal variation in wind speed affects the value assigned to the depth (1) of the boundary layer; the diurnal variation in the radiation (energy) income at the ground surface affects the temperatures experienced in the air and in the soil and the associated vapour pressures exerted by the moisture in the free air, and in the soil. Because of the coupling of temperature and vapour pressure gradients in the situation under discussion and the movement of water vapour down both temperature and moisture vapour gradients, even the apparent uniform behaviour of the soil moisture in the first soil layer (phase 1 drying, with $\Sigma D \leqslant 25$mm) hides a great range of situations. The relation between ϕ, the diffusion coefficient in porous soil and ϕ_0, the diffusion coefficient of water vapour in free air is complex and is discussed, for example, in a limited fashion by Rose (1966).

The point to be made at this time is that whilst meteorological physics may be an exact science, and may provide a quantitative insight into the mechanisms involved in the physical processes under examination, any transfer to the field situation must involve approximations to precise theory. These approximations are inevitable, since somewhat idealised constraints will have been set up to develop the theory; these constraints are unlikely to be met in the real situation, the critical field conditions are unlikely to be specified in sufficient detail, and not least, the variability of natural materials such as soils, or the spatial variation of rainfall must raise the question of the representativeness of a given site.

A more detailed theoretical treatment could be attempted than has been given in this note. If such a treatment does not constitute an end in itself, then simple working solutions, such as have been presented, are all that can be justified.

7. References

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Agricultural Memorandum No 580 - II

ON THE MOVEMENT OF WATER FROM THE SOIL

- A synopsis and commentary on some field data.

C V Smith

II UNDER GRASS

1. SHORT TURF

The data made available in the Rothamsted Report (1972) for the years 1963, 1964, are sparse; in effect they offer only the bald statement that over 2 separate monthly periods, when there was no drainage, the measured totals of rainfall (R) and changes in soil moisture content (D) were equal to the potential transpiration (E_T).

For the 1971 season, the Rothamsted report does not present moisture inputs and soil moisture changes in the same manner and detail as for other crops ie weekly figures are not shown. The emphasis is on the seasonal water balance, and though a graph [Fig 1 (III) - Rothamsted numbering] shows cumulative values of E, the actual transpiration, and E_T, figures relating to the water balance over short periods are avoided.

Attention has already been drawn to the internal evidence of the Rothamsted Report [Table 5 (I)] that such cumulative totals smooth out large variations in the ratio E/E_T over short periods.

This emphasis on the seasonal water balance means that we can obtain little fresh information on the short-term evaporative response of the crop to soil moisture stress ie on the decline of transpiration, E, below the potential transpiration, E_T, or the soil moisture deficit at which such a decline sets in.

2. FIELD GRASSES

Information is presented in the Rothamsted Report (1972) on changes in soil moisture, in 30 cm layers down to 90 cm, both for Timothy and the deeper rooting Meadow Fescue.

Fig 3 (III) - Rothamsted numbering - indicates:

a. that a 90 cm depth may not always be completely adequate to study the moisture changes under grass

b. the role of 'root density' in determining the water extraction from a given soil layer, eg the shorter rooting Timothy extracts more soil moisture from the top 30 cm layer than the deeper rooting Meadow Fescue. This relative water extraction by the two grasses is reversed in the layers 30-60 cm, 60-90 cm from the soil surface; however, the total of water extracted from soil reserves is much the same in both cases, as might be expected in an initial, simple first drying of the soil.

The basic data presented by Rothamsted is shown in Table 3 (III).

Table 3 (III)
Grass 1964. Curtailed water balance (mm)

Period	R	Nominal	Average Drying $\bar{D}$						
		I	F_O	T_O	F_I	T_I	$(R+\bar{D}_O)$	$(R+I+\bar{D}_I)$	$\sum E_T$
1. 15/6 – 3/7	37	–	?		?		46?	46?	46
2. 3/7 – 28/7	31	–	37	44	37	35	71	67	120
3. 28/7 – 13/8	3	51	29	34	– 6	– 2	35	50	165
4. 13/8 – 27/8	9	25	17	16	– 6	– 3	26	30	193
5. 27/8 – 28/9	19	–	16	10	55	58	32	75	253
6. 28/9 – 9/10	12	–	–14	–13	– 7	– 8	– 1	4	264
7. 9/10 – 25/11	35	–	–24	–24	–24	–24	11	11	275

where R = rainfall
I = irrigation (or irrigated plots when I is a suffix)
F = fescue
T = timothy
O = suffix to indicate unirrigated plots
D = soil drying
$\sum E_T$ = accumulated potential transpiration.

This information may also be presented in the form shown in Table 3 (III) A.

Table 3 (III A)

Period	R	I	$\bar{D}_O$	$\bar{D}_I$	E_T	E_O	E_I	E_O/E_T	E_I/E_T
1	37	–	?	?	46	?	?	?	?
2	31	–	40	36	74	71	67	.96	.89
3	3	51	32	– 4	45	35	50	.78	1.11
4	9	25	17	– 4	28	26	30	.93	1.07
5	19	–	13	56	60	32	75	.53	1.25
6	12	–	–13	– 8	11	– 1	4	negative	.36
7	35	–	–24	–24	11	11	11	1.00	1.00

E_O = evaporation from non-irrigated plots
E_I = evaporation from irrigated plots

2.1 Before any conclusion concerning a general model for soil water extraction is attempted, it is suggested the above data should be smoothed.

PERIOD 6

To remove the anomaly of a negative value of E_O/E_T, we assume that in this period

$$E_I = 1.1\ E_T = 12 \text{ mm}$$
$$E_O = E_T = 11 \text{ mm}$$

PERIOD 5

If the same net drying is maintained over periods 5 and 6, then in period 5

$$D_O = 25; \quad D_I = 64$$

$$E_O/E_T = .73; \quad E_I/E_T = 1.39$$

We note that E_I/E_T in period 5 is still in excess of the general run of values shown in Table 3 (III) B below, where the modifications outlined here are incorporated.

Overestimate of the soil drying in period 5 could arise either, from an overestimate of the soil moisture in the rewetting phase of periods 3 and 4 (and from exterior flooding of the probe access tube on the irrigated plots), or, from an underestimate (the ignoring) of through drainage in periods 3 and 4, into layers below the 90 cm level.

Table 3 (III B)

Period	R	I	$\bar{D}_O$	$\Sigma \bar{D}_O$	$\bar{D}_I$	E_T	E_I	E_O	E_O/E_T	E_I/E_T
1	37	-	?	?	?	46	46	46	1.00	1.00
2	31	-	40	40	36	74	67	71	.96	.89
3	3	51	32	72	- 4	45	50	35	.78	1.11
4	9	25	17	89	- 4	28	30	26	.96	1.07
5	19	-	25	114	64	60	74	44	.73	1.39
6	12	-	- 1	113	0	11	12	11	1.00	1.11
7	35	-	-24	89	-24	11	11	11	1.00	1.00

In our search for information on the general rate of transpiration we may now suggest.

i. Under conditions of no soil moisture stress (irrigated plots)

a. a typical value of the ratio E_I/E_T might be of the order 1.0 (over the whole season, $E_I/E_T = 1.03$)

b. when the grasses are tall (20-30 cm), a more representative value of E_I/E_T might be of the order 1.1.
This statement is based on the supplementary information on crop height at various dates through the season which is given in the Rothamsted Report.

ii. Under conditions of soil moisture stress the decline in the ratio E_O/E_T takes place at a soil moisture greater than 89 mm, cf period 4. [It has to be remembered that D is the accummulated drying from the time of first monitoring. The absolute deficit may be greater than D, depending on the initial soil moisture deficit.
The low value of the ratio E_O/E_T in period 3 is ignored, since the ratio recovers to a value close to unity in period 4, even though rainfall in periods 3 and 4 is small].

3. MODELS OF BEHAVIOUR

Various models of soil moisture extraction under grass are now in current use.

3.1 That set out in MAFF Technical Bulletin No 16 assumes that

$E = E_T$ until $\Sigma D = 50$ mm

$E = 0.5\, E_T$ when $100\ \text{mm} > \Sigma D > 50\ \text{mm}$

$E = 0.25\, E_T$ when $125\ \text{mm} \geq D > 100\ \text{mm}$

A maximum deficit of 125 mm is assumed.
Current rainfall is removed preferentially at a rate $E = E_T$. Soil moisture reserves and soil moisture deficits must be fully removed from the top soil layer before the second, and subsequently the third soil layers are acted upon.

6. Under grass, the readily available water (at field capacity) in the various soil layers and in various soil types are taken to be.

Layer	Heavy	Medium	Light Soil
0-30 cm	60 mm	45 mm	30 mm
30-60 cm	35	25	20
60-90 cm	35	25	20
90-120 cm	10	10	10

5. REFERENCES

Penman, H L 1962 Woburn irrigation 1951-59 II. Results for grass J Agric Sci Camb 58, 349-64

Smith, L P 1967 Potential Transpiration MAFF Tech Bull No 16

Meteorological Office
Cambridge

November 1973

EIW/

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AGRICULTURAL MEMORANDUM NO 580-III

ON THE MOVEMENT OF WATER FROM THE SOIL

- a synopsis and commentary on some field data

C V Smith

III CEREALS

1. The data available for examination are those to be found in the Rothamsted Report for 1972, and those collected by the Meteorological Research Unit on the site of the Plant Breeding Institute at Cambridge.

The Cambridge data are based on both neutron probe and lysimeter measurements. Some published information is to be found in Grant (1970). Other unpublished data from Cambridge, for the years 1967 and 1970 are also included in the discussion.

2. It is at once apparent that the total of data do not fall into consistent and reproducible patterns from season to season; neither are the differences found to be explained simply in terms of the available water in the soils on the different sites, nor simply in terms of the soil moisture deficit at a particular stage of crop growth.

3.1 One area of agreement is that the depth of soil that needs to be studied to follow changes in soil moisture under cereals is of the order 1.5 metres. Where examination was restricted to the top 90cm, both sets of experimenters report difficulties, due to the cereal crop rooting into the bottom of the layer under investigation.

3.2 A common feature of the 7 Rothamsted results is that the ratio E/E_T (where E = actual transpiration, E_T= potential transpiration), is greater than 1.0, over a substantial part of the growing season i.e mid May to mid July, (Growth Stage 7 - 11.2, say). For the 6 spring sown and 1 winter sown crops, the reported range is of the order 1.1 to 1.3. Those figures are based on the smoothed data provided by cumulative totals of E and E_T, but again, the internal evidence of the Rothamsted figures is that over short (weekly) periods, the range of E/E_T may be from 0.7 to 1.7.

By contrast, the Cambridge data do not always show this excess of E over E_T, when cumulative totals are examined.

In 1967 and again in 1969, a strict equality between E and E_T is shown for a spring sown barley until mid-July (Growth Stage 11.2 say).

In 1968 at Cambridge however, again for a spring sown barley, data approximating to that found at Rothamsted are reported. From the time of first monitoring in late April until late May (up to Growth Stage 9) cumulative totals indicate $E=E_T$. From late May until early July (up to Growth Stage 11.1) the ratio E/E_T is indicated as 1.38.

In 1970 at Cambridge, a variety of modes of behaviour is reported. On irrigated plots during May (Growth Stage 5 - Growth Stage 10) the ratio E/E_T was found to be 0.5 from lysimeter measurements and 0.75 from neutron probe measurements. Over the period through June to mid July (Growth Stage 10 - Growth Stage 11.1), the ratio E/E_T determined by these respective measurements was 1.11 and 1.35. By contrast, on non irrigated plots, in which the soil moisture deficit rose steadily from around zero in mid-May (Growth Stage 8) to a peak value of around 100 mm in the second half of June (Growth Stage 10.5.3+), E/E_T remained below unity at all times, a ratio of 0.57 being found with lysimeters, a ratio of 0.86 being found with the neutron probe.

The instrument errors and difficulties experienced are discussed at length in the original publications. There seems little point in reproducing the findings here.

The general weight of the evidence would appear to be that over sensible periods (somewhat greater than 1 week), the ratio E/E_T for cereals during a significant part of their growing season (Growth stage 7 to Growth Stage 11.1) is likely to exceed unity and to be in the range 1.1 to 1.3.

This statement holds for both irrigated and unirrigated crops on medium to heavy soils in the East of England, and to that extent would appear to be independent of the magnitude of the soil moisture deficit under the crop in a typical sample of years.

Nevertheless both the Rothamsted and Cambridge data indicate a departure point in some seasons at which E/E_T for unirrigated plots is below that for irrigated plots. In some, possibly most situations, there would appear to be a ready explanation in terms of the relative growth stages of the irrigated and unirrigated crops, the irrigation favouring the maintenance of the later vegetative growth stages and a more slowly maturing crop - a delay of up to 10 days being reported at the ripening stages and at senescence. Such was the case at Rothamsted in 1970.

1970 is also the year when some further comment on the Cambridge data is called for. If the non-irrigated lysimeter readings are rejected (one understands there may have been some positive pumping of the lysimeter), then the non-irrigated field plots studied by the neutron probe begin to fall below the water usage of the irrigated plots after mid-June (Growth Stage 10.5.1 - 10.5.2 +0. Noting the more or less complete absence of rainfall between early May and the end of June, and a soil moisture deficit of the order 80 mm in the latter half of June, it would seem reasonable to infer a significant difference in the Growth Stages of the irrigated and non-irrigated crops at Cambridge as well as Rothamsted.

We make the suggestion now that with the soil moisture reserves normally available at the start to the growing season in Eastern England, one response to large soil moisture deficits later in the season is, by cereals, simply the acceleration of the transition from one phase of growth to the next. This irreversible response to large soil moisture deficits, and possibly soil moisture stress, would seem to distinguish cereals somewhat from many other crops; the change from one stage of growth to the next would, for cereals, automatically entail and accomodate a lowering of plant water demand, and we may not always separate cause and effect. It would also suggest that a more convenient indication to changing transpiration rates for cereals might be the stage of growth, rather than has been adopted elsewhere in this note, the arrival at certain critical soil moisture deficits.

4. The maximum depletion of soil moisture reserves in the heavy Rothamsted soil under cereals was approximately as given below. Those for other soil types are estimates.

	Heavy Soil	Medium Soil	Light Soil
0-30 CM layer	60 mm	45 mm	30
30-60	35	25	20
60-90	35	25	20
90-120	20	15	10
120-150	10	10	5
Total	160	120	85

5. The suggested mode of water usage by cereals is as follows.

5.1 Between emergence and mid-April, the water loss is much as that from bare soil (see this Memorandum - Part I).

5.2 Over the second half of April, (up to Growth Stages 5), water is removed at the potential transpiration rate, E_T.

5.3 During May and June, (Or up to Growth Stage 10.5.4 if this is reached before the end of June), water is removed at 1.20 E_T.

5.4 During July (up to Growth Stage 11.2), water is removed at the potential transpiration rate, E_T.

5.5 After Growth Stage 11.2, the water removed from the soil up to the time of harvest is neligible.

5.6 In any period under examination, current rainfall is removed preferentially before soil moisture reserves are modified in any way.
The soil moisture reserves available in the three broad soil types are 160, 120, 85 mm respectively. When these are exhausted, there is a further depletion at a nominal rate of 0.1 E_T.

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Cambridge
November 1973

6. References

GRANT, D R 1970 Some measurements of evaporation in a field of barley.
J Agric. Sci., Cambridge. 75, 433-443

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AGRICULTURAL MEMORANDUM NO.580 - IV

ON THE MOVEMENT OF WATER FROM THE SOIL - A synopsis and commentary on some field data.

C V SMITH

IV POTATOES

1. The practice of ridging potatoes introduces difficulties in the use of the neutron probe with this particular crop. The inter-row spacing of the plants is then greater than the sensing range of the instrument, part of the surface layer being examined by a probe inserted in a ridge is "free air" and not soil, and thirdly, once some ground cover is established, rain water tends to be shed into the furrows, whilst the ridges are relatively sheltered. To produce a seasonal water balance, it was found necessary on the Rothamsted site to weight the observed drying of the top 20 cm of "soil" by a factor 2/3. The observed drying of soils below the top 60 cm was minimal for both unirrigated and irrigated crops.

The basic Rothamsted data is shown in Table 5(II)

TABLE 5(II)

POTATOES, 1969. WATER BALANCE AND PROBABLE EVAPORATION (mm)

		Unirrigated Plots				Irrigated Plots				
	Period	R	D1	D2	R+ΣD	I	D1	D2	R+I+ΣD	ΣET
1	5/6–10/6	0.0	4.8	–2.6	2.2	–	4.5	0.6	5.1	17
2	10/6–17/6	4.8	No Reading		–	–	8.5	9.4	22.7	40
3	17/6–20/6	11.2	8.3	10.9	35.2	29.9	–13.4	–8.1	8.7	47
4	20/6–26/6	15.5	–0.8	1.2	15.9	–	2.8	–1.8	16.5	61
5	26/6– 4/7	0.3	8.3	7.1	15.7	23.3	7.9	8.4	37.5	91
6	4/7–11/7	25.4	–3.7	6.1	27.8	–	–6.0	2.5	21.9	106
7	11/7–18/7	0.0	4.4	7.4	11.8	26.8	9.2	2.6	27.5	128
8	18/7–25/7	0.0	2.6	11.4	14.0	25.3	–8.6	7.3	23.8	150
9	25/7– 1/8	25.4	–9.1	–3.9	12.4	–	–0.7	–1.6	23.1	162
10	1/8– 8/8	16.2	1.0	0.4	17.6	–	5.5	–1.7	20.0	180
11	8/8–14/8	4.6	4.2	8.2	17.0	23.7	–8.4	–4.7	15.1	195
12	14/8–28/8	22.6	–1.5	5.3	26.4	–	5.4	10.4	38.4	226
13	28/8– 3/9	0.3	2.0	1.8	4.1	–	2.8	–0.8	2.3	236
14	3/9–12/9	0.2	1.1	2.9	4.2	–	1.4	0.9	2.5	246

Where R = Rainfall
D_1 = 2/3 Measured drying in layer 0–20 cm.
D_2 = Measured drying in layer 20–150 cm.
I = Irrigation
E_T = Potential Transpiration
Σ = Accumulated total

These data may be rearranged to give the information set out in Table 5(II)A

TABLE 5(II)A

Period	Eo	Do	ΣDo	R	I	E_I	D_I	ΣD_I	E_T	Eo/E_T	E_I/E_T
1	2.2	2.2	2.2	0	-	5.1	5.1	5.1	17	.13	.30
2	-	-	2.2	4.8	-	22.7	17.8	22.9	23	-	1.0
3	35.2	19.2	21.4	11.2	29.9	8.7	-21.5	1.4	7	1.17	1.24
4	15.9	0.4	21.8	15.5	-	16.5	1.0	2.4	14	1.13	1.19
5	15.7	15.4	37.2	0.3	23.3	37.5	16.3	18.7	30	.52	1.25
6	27.8	2.4	39.6	25.4	-	21.9	3.5	22.2	15	1.85	1.45
7	11.8	11.8	51.4	0	26.8	27.5	11.8	34.0	22	.54	1.25
8	14.0	14.0	65.4	0	25.3	23.8	- 1.3	32.7	28	.50	1.08
9	12.4	-13.0	52.4	25.4	-	23.1	- 2.4	30.3	12	1.03	1.93
10	17.6	1.4	53.8	16.2	-	20.0	- 3.8	26.5	18	.98	1.11
11	17.0	12.4	66.2	4.6	23.7	15.1	- 3.7	22.8	15	1.13	1.0
12	26.4	2.8	69.0	22.6	-	38.4	15.8	38.6	31	.82	1.24
13	4.1	3.8	72.8	0.3	-	2.3	2.0	40.6	10	-	-
14	4.2	4.0	76.8	0.2	-	2.5	2.3	42.9	10	-	-

The Suffix 0 indicated unirrigated crops

The Suffix I indicated irrigated crops

Supplementary information provided is that the initial soil moisture deficit before the first monitoring was of the order 10 mm. Subsequent soil moisture changes are of course taken from a zero at the first monitoring.

At the time of the first monitoring there was about 25% ground cover. By 4 July (end of period 5) the unirrigated plants were wilting. Leaves were yellowing at the end of August (Period 12).

At the transpiration check first shown in Period 5, the absolute soil moisture deficit at the beginning of this period is of the order 22+10 = 32 mm for the unirrigated crops. The rate of water usage is around 0.5 E_T. Confirmation of this rate is given in Periods 7 and 8. Those of period 6 are complicated by the inclusion of through drainage in the value assigned to Eo. With a full crop cover established, the ratio E_I/E_T is generally >1. The extent of the soil drying in period 11 is not consistent with that experienced earlier in the season.

Data for other years in the Rothamsted series of experiments add little to the information set out above, either because of weather and instrumentation difficulties or because of difficulties with the crop. A general summary of their results is shown below.

Year	Depth	Z	Do	E/E_T
1965	90 cm	60 cm	≥ 25 mm	1.0
1966	90	60	≥ 25	1.05
1966	99	60	≥ 20	1.05
1968	150	60	15	1.05
1969	150	<90	25	1.25
1971	150	>90	35	1.1

Depth = depth of monitoring.

Z = Approximate maximum depth of drying in unwatered plots.

Do = estimate of maximum drying in the profile before there was a detectable check to transpiration.

E/E_T = monitored over the main growing period.

2.- The suggested mode of water usage by potatoes is as follows:

2.1 The water available as soil reserves at field capacity in the three broad soil classes are taken to be

Layer	Heavy Soil	Medium Soil	Light Soil
0–30 cm	60 mm	45	30
30–60 cm	35 mm	25	20

These figures are for level soil.

Because of the ridging adopted for the potato crop, the available soil moisture has to be reduced. Using the Rothamsted weighting of 2/3 for the water reserves available in the top 20 cm of soil, the total water reserves in the top 60 cm of soil are taken to be

Layer	Heavy Soil	Medium Soil	Light Soil
0–60 cm	80 mm	60 mm	45 mm

2.2. During April, the water loss is much as from bare soil (see this Memorandum – Part I). Water is lost at the potential transpiration rate E_T, until such times as a deficit of the order 25 mm is established. Thereafter, there is a transpiration check and further water is lost at a nominal $0.1E_T$.

2.3. During May, when a crop cover is being established, water may again be lost from the soil at the potential transpiration rate until such times as a deficit of the order 25 mm is established. Thereafter, there is a transpiration check, but now the remaining soil reserves in the 0–60 cm layer may be drawn on at a rate equal to $0.5\ E_T$.

2.4. From the beginning of June to the end of August, water may be removed from the soil at a rate equal to $1.1\ E_T$, until such times as a deficit of the order 30 mm is established. Thereafter, there is a transpiration check, but remaining soil reserves in the 0–60 cm layer may be drawn on at a rate equal to $0.5\ E_T$.

2.5. In any period for which a water balance is being drawn up, current rainfall is removed preferentially (at a rate equal to E_T or $1.1\ E_T$, depending on the month) before soil moisture reserves are modified in any way.

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AGRICULTURAL MEMORANDUM NO 580-V

ON THE MOVEMENT OF WATER FROM THE SOIL

A Synopsis and commentary on some field data - C V SMITH

V - Under Sugar Beet

1. The data available for examination are those contained in the Rothamsted Annual Report (1972) and in Draycott and Durrant (1971) - J. Agric. Sci. Camb. 76,277-282.

2. Rothamsted give details of single experiment which is reported in Tables 4 (I) and 5 (I) (Rothamsted notation)

TABLE 4 (I)

WATER BALANCE (MM): SUGAR BEET 1970

		Drying D_o				Probable E_o			
Period	Rain	Site 1	Site 2	Site 3	Site 4	Site 1	Site 2	Site 3	Site 4
1	1.0	9.7	10.9	17.0	13.3	13.8	13.8	13.8	13.8
2	7.6	14.1	12.9	11.3	12.9	20.4	20.4	20.4	20.4
3	6.1	12.0	10.2	12.5	9.3	17.1	17.1	17.1	17.1
4	4.1	4.2	5.8	7.5	5.1	14.7	14.7	14.7	14.7
5	11.4	8.8	14.5	9.4	10.3	22.2	22.2	22.2	22.2
6	13.5	7.8	11.2	10.8	10.7	23.7	23.7	23.7	23.7
7	7.4	8.6	9.6	4.6	16.6	14.0	14.0	20.5	20.5
8	15.8	2.6	7.3	6.4	- 0.1	20.3	20.3	19.4	19.4
9	-	15.8	24.9	12.9	28.1	14.4	14.4	26.5	26.5
10	25.2	- 5.7	- 7.2	2.0	- 7.1	23.4	23.4	18.0	18.0
11	38.7	- 17.8	- 13.9	- 16.5	- 5.0	21.5	21.5	28.3	28.3
12	2.0	15.7	17.1	18.2	21.8	19.0	19.0	21.4	21.4
13	9.4	11.4	9.8	1.7	18.9	16.0	16.0	23.8	23.8
14	36.9	- 29.6	- 13.7	- 21.0	- 29.2	11.6	11.6	15.5	15.5
15	-	20.3	12.9	12.4	20.1	16.4	16.4	16.5	16.5
16	8.9	11.6	6.0	8.6	13.7	18.9	18.9	18.7	18.7

Where D_o = soil drying on unirrigated plots

E_o = evaporation on unirrigated plots

TABLE 5 (I)

WATER BALANCE (MM): SUGAR BEET, 1970

		Accumulated E_o		Accumulated E_T
	Period	Site 1 and 3:	Site 2 and 4:	
1	5–16/6	14	14	39
2	16–23/6	34	34	62
3	23–29/6	51	51	82
4	29/6–3/7	66	66	94
5	3–10/7	88	88	112
6	10–16/7	112	112	129
7	16–23/7	126	132	145
8	23–30/7	146	152	159
9	30/7–5/8	161	178	176
10	5–12/8	184	196	190
11	12–26/8	206	225	216
12	26/8–1/9	224	246	228
13	1–10/9	240	270	243
14	10–21/9	252	285	259
15	21–28/9	268	302	266
16	28/9–12/10	287	321	279

where E_T = potential transpiration

The data of Tables 4 (I) and 5 (I) may be reorganised to provide the information set out in Table 4 (I) A.

TABLE 4 (I) A

WATER RELATIONSHIPS (MM): SUGAR BEET, 1970

	Accumulated Drying D_o				E_o		E_T	E_o/E_T	
Period	Site 1	3,	2,	4.	Site 1 and 3	2 and 4		Site 1 and 3	2 and 4
1	9.1	17.0	10.9	13.3	13.8	13.8	39	.36	.36
2	23.8	28.3	23.8	26.2	20.4	20.4	23	.89	.89
3	35.8	40.8	34.0	35.5	17.1	17.1	20	.85	.85
4	40.0	48.3	39.8	40.6	14.7	14.7	14	1.05	1.05
5	48.8	58.7	54.3	50.9	22.2	22.2	18	1.23	1.23
6	56.6	69.5	65.5	61.6	23.7	23.7	17	1.39	1.39
7	65.2	74.1	75.1	78.2	14.0	20.5	16	.87	1.28
8	67.8	80.5	82.4	78.1	20.3	19.4	14	1.45	1.38
9	83.6	93.4	107.3	106.2	14.4	26.5	17	.85	1.56
10	77.9	95.4	101.1	99.1	23.4	18.0	14	1.67	1.28
11	70.1	78.9	87.2	94.1	21.5	28.3	26	.83	1.09
12	85.7	97.1	104.3	115.9	19.0	21.4	12	1.58	1.78
13	97.1	98.8	114.1	134.8	16.0	23.8	15	1.07	1.58
14	67.5	77.8	110.4	105.6	11.6	15.5	16	.73	.97
15	87.8	90.2	123.3	125.7	16.4	16.5	7	2.35	2.36
16	99.4	98.8	129.3	139.4	18.9	18.7	13	1.45	1.44

Crop details noted are that it was sown on April 24, emerged about 5 May and was singled on 28-31 May. Irrigated crops achieved a full ground cover before the unirrigated crop to which the data above refers. For the unirrigated crops, complete cover was attained around mid-July ie by the end of period 6.

Comment has been made elsewhere (Cf Bare Soil - Part I) on the need to smooth the values E_o/E_T by considering longer periods for E_T than the intervals between the weekly neutron probe measurements. Bearing this point in mind, then Table 4 (I) A suggests that in fact no transpiration check was established on the heavy (clay with flint) soil at Rothamsted up to soil moisture deficit of around 140 mm. This figure of 140 mm is a relative change from the time of the first neutron probe reading, and the absolute soil moisture deficit, that this heavy land can sustain under sugar beet must presumably be at least 150 mm.

A further point to emerge from Table 4 (I) A is that a mean value for the ratio E_o/E_T is of the order 1.3.

Other information that may be culled from the Rothamsted Report is that the maximum soil moisture change observed in successive 30 cm layers; under unirrigated sugar beet in 1970 was as follows:-

0-30 cm	50 mm
30-60 cm	40 mm
60-90 cm	20 mm
90-120cm	20 mm
120-150cm	10 mm

3. The work carried out by Draycott and Durrant was at Broom's Barn. The most interesting results are presented in graphical form and relate to experiments in the three years 1967, 68, 69. The information we require is not discussed explicitly but we may derive the following:

In the three years, after a full ground cover was established (July onwards), the ratio E/E_T for crops which did not suffer a transpiration check was respectively 1.1; 1.25; 1.20.

On the Broom Barn soil, a transpiration check was established at around 125 mm (5 inches) in the total soil depth (110 cm) that was examined.

After the transpiration check, water was removed at a rate equal approximately to 0.6 E_T.

The soil water reserves removed by sugar beet at Brooms Barn in the driest of the three years (1967) was approximately

0-30 cm layer	60 mm
30-60	50 mm
60-90	50 mm
90-120	40 mm

The soil type on which this particular experiment was carried out is not given in the published information but comparison with the water removed by both sugar beet and cereals at Rothamsted would suggest we are dealing with a heavy (Stretham?) soil type at Brooms Barn, rather than the more typical sandy loams.

4. The suggested mode of water usage for sugar beet is as follows:

4.1 The soil reserves at field capacity available to sugar beet on the three broad soil types are taken to be:

Layer	Heavy Soil	Medium Soil	Light Soil
0-30 cm	60	45	30
30-60 cm	50	40	25
60-90 cm	50	40	25
90-120cm	40	30	20
120-150cm	10	10	10

4.2 During April and May, the land may lose water at the potential rate E_T, until such times as a deficit of the order 25 mm is established. At this point there is an evaporation check and further water is lost at a nominal rate equal to 0.1E_T.

4.3 During June, the land may lose water at the potential rate E_T until such times as a deficit of the order 25 mm is established. At this point, there is a transpiration check and further water is lost at a rate equal to 0.5 E_T.

4.4 In the months of July through to the end of October, the reserves in the layer 0-150 cm may be drawn on, and water will be removed at a rate equal to 1.25 E_T, until such times as reserves in the layer 0-90 cm are exhausted. There will be a transpiration check at this point, and further soil moisture (from the lower horizons) will be removed at a rate equal to 0.6E_T until such times as all the reserves in the layer 0-150 cm are exhausted.

4.5 In any period for which a moisture balance is being struck, current rain fall will be removed preferentially (at a rate equal to E_T or 1.2E_T depending on the month), before soil moisture reserves are modified in any way.

MINISTRY OF AGRICULTURE, FISHERIES AND FOOD

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AGRICULTURAL MEMORANDUM NO 580 - VI

On the Movement of Water from the Soil - a synopsis and commentary on some field data

VI - Under kale

C V Smith

1. The 1968 data from Rothamsted refer to a wet season. The maximum drying observed in a total soil depth of 120-150 cm is 9 mm. It is evident that no transpiration check should have been expected and almost the only information relevant to a general model of water usage is that the ratio $E/E_T \simeq 1.2$ (where E = transpiration; E_T = potential transpiration).

In 1967, we may, from the data of Rothamsted Table 10 (III), infer a range of values of the ratio E/E_T of 1.2 to 1.8 over periods of the order 1 month. A suggested mean (by Rothamsted) is $E/E_T = 1.3$

The comparison of soil moisture data for the 1967 and 1971-72 seasons suggest an initial (absolute) soil moisture deficit of 15 mm in the top 30 cm layer at the time of first monitoring with the neutron probe on 4 July 1967. The additional maximum soil moisture losses in the 1967 season in the various layers are indicated (under kale on the heavy Rothamsted soil) as:-

0-30 cm	40 mm
30-60 cm	30 mm
60-90 cm	25 mm
90-120 cm	20 mm
120-150 cm	10 mm

The maximum (absolute) soil moisture deficit sustained in the 1967 season occurred in July. This was of the order 125 mm. There is no reported check to crop growth and the ratios E/E_T (1.2-1.6) on the individual sites would not seem to indicate any transpiration check whilst such a soil moisture deficit was being developed.

A point possibly of significance in interpreting the 1971 observations is that in 1967 the crop did not begin to draw on soil reserves below the 30 cm level until mid to late July, when the absolute soil moisture deficit in the top 30 cm was around (35 + 15) = 50 mm and the stage of crop growth was indicated by rather more than a 50% ground cover.

The data made available for 1971 is shown in Table 11 (III).

Table 11 (III)

Kale, 1971 Probable evaporation (mm)

Period		R	E	ΣE_T
1	17/5–26/5	17	14	23
2	26/5–3/6	6	11	47
3	3/6–17/6	57	(22)	69
4	17/6–23/6	41	(22)	88
5	23/6–28/6	5	23	103
6	28/6–5/7	2	25	127
7	5/7–12/7	0	30	152
8	12/7–19/7	0	33	176
9	19/7–26/7	3	24	191
10	26/7– 9/8	43	36	224
11	9/8–17/8	21	23	238
12	17/8–25/8	5	18	252
13	25/8– 6/9	6	21	274
14	6/9–16/9	0	17	290
15	16/9–23/9	0	13	298
16	23/9–30/9	13	8	306
17	30/9–11/10	1	10	314
18	11/10–22/10	72	?	319

( ) indicates estimated values

R = Rainfall
E = Evaporation
ΣE_T = Accumulated potential transpiration

The supplementary data shown in Table 11 (III)A may be deduced, given initial (absolute) soil moisture deficit of 8 mm, at the time of the first monitoring by neutron probe.

Table 11 (III)A

Kale, 1971 Soil moisture balance (mm)

Period	R	E	D	Accumulated drying $\sum D$	E_T	E/E_T
1	17	14	− 3	5	23	0.58
2	6	11	5	10	24	0.46
3	57	22	− 35	0	22	1.00
4	41	22	− 19	0	19	1.15
5	5	23	18	18	15	1.53
6	2	25	23	41	24	1.04
7	0	30	30	71	25	1.20
8	0	33	33	104	24	1.37
9	3	24	21	125	15	1.60
10	43	36	− 7	118	33	1.09
11	21	23	− 2	116	14	1.64
12	5	18	− 13	103	14	1.28
13	6	21	− 15	88	22	0.95
14	0	17	17	105	16	1.06
15	0	13	13	118	8	1.63
16	13	8	− 5	113	8	1.00
17	1	10	− 9	104	8	1.25
18	72	?	?		5	?

D = soil drying

The above data refer of course to an unirrigated crop. Other information provided is that at the time of the first monitoring the crop was 5 cm tall and ground cover about 2%. That portion of the crop that was subsequently to be irrigated (over periods 7,8 and 9) grew very uniformly, attaining a full cover early in July and a height of 100 cm by the end of July, with a slow increase later. In contrast, the unirrigated crop, even before irrigation was applied elsewhere, was showing less uniform growth, both in height and fractional cover. The absence of irrigation clearly retarded growth in July (periods 6–10) and it was early August (period 10–11) before the unirrigated plants attained full cover and the end of August (period 13) before they reached a maximum height of 70–80 cm.

On the basis of Table 11 (III)A, and what must now be regarded as typical variations in the ratio E/E_T over periods of under one week, it is difficult to identify any transpiration check over periods 6–9 which correlates with the visual observations on crop and relative crop performance over this time. The evidence of Table 11(III)A is that soil moisture reserves below the 30 cm level were being drawn upon from period 7 onwards, well before a full ground cover was established: one inference is that the normal balance between root and shoot development was interfered with by the depletion of soil moisture reserves in the normal rooting zone applicable to the early stages of growth and that root development was required to take precedence over the above ground parts of the plant. Despite the visual evidence of a check to plant growth, water usage does not appear to have been altered at this time.

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Agricultural Memorandum No 580 – VII

On the movement of water from the soil

– a synopsis and commentary on some field data

C V Smith

VII – Under field beans

1. The basic information is supplied by the Rothamsted Report (1972) on the 1970 growing season.

During this time, a soil moisture stress developed on unirrigated plots, as indicated by the visual evidence of wilting, a rapid senescence, and a decline in the ratio E/E_T, (where E = evapo-transpiration, E_T = potential transpiration).

Over the season, root activity would appear to have been limited primarily to the 0–60 cm layer; the average, maximum changes in soil moisture (on the heavy Rothamsted clay soil) were found as follows

0–30 cm layer	55 mm
30–60	30
60–90	10
90–120	not significant
120–150	not significant

A water balance for the season is reproduced in Table 3(I) [Rothamsted numbering].

TABLE 5 (I)

WATER BALANCE (MM): SUGAR BEET, 1970

		Accumulated E_o		Accumulated E_T
	Period	Site 1 and 3:	Site 2 and 4:	
1	5-16/6	14	14	39
2	16-23/6	34	34	62
3	23-29/6	51	51	82
4	29/6-3/7	66	66	94
5	3-10/7	88	88	112
6	10-16/7	112	112	129
7	16-23/7	126	132	145
8	23-30/7	146	152	159
9	30/7-5/8	161	178	176
10	5-12/8	184	196	190
11	12-26/8	206	225	216
12	26/8-1/9	224	246	228
13	1-10/9	240	270	243
14	10-21/9	252	285	259
15	21-28/9	268	302	266
16	28/9-12/10	287	321	279

where E_T = potential transpiration

The supplementary data shown in Table 3 (I) A may be deduced

Table 3 (I) A

Water Balance (mm): Field Beans, 1970

	Accumulated drying			Accumulated Drying	
Period	Site 1	2	E_O/E_T	Site 3	E_I/E_T
1	0.5	2.1	.84	- 3.3	.65
2	7.1	9.2	.46	6.0	.47
3	23.4	18.4	1.09	15.7	.87
4	32.6	27.3	.65	8.6	.73
5	58.9	52.0	1.06	27.9	1.33
6	79.3	67.7	.83	40.8	1.37
7	93.5	84.5	.73	43.4	1.00
8	92.5	88.2	.56	39.6	1.11
9	103.7	99.7	1.11	52.0	1.19
10	102.6	103.4	.69	37.2	1.52
11	83.9	89.8	.35	33.9	.83
12	86.5	93.5	.87	46.7	1.34
13	74.9	81.7	.48	25.3	.92
14	61.0	55.7	.38	15.0	.86
15	67.6	55.2	.23	28.6	.71
16	27.0	26.0	.97	4.7	.55

In the Tables,

R = rainfall
I = irrigation
O, as a suffix, denotes unirrigated plots
I, as a suffix, denotes irrigated plots
E = transpiration
E_T = potential transpiration
D = soil drying

Some comment on the stages of crop growth is now relevant.

The crop was drilled on March 27 and emerged about 24 April. Growth was steady and up to the middle of period 6, the appearance was the same on both irrigated and unirrigated plots - the crops were about 50 cm tall, with about 50% cover and a leaf area index of about 2.5. After that the irrigated plants continued to grow until the end of July (period 12), reaching a height of 120 cm, a cover of almost 100% and a leaf area index near 5. Meantime the unirrigated plants grew little. They reached a height of 65 cm only; cover decreased to a little below 50%, fluctuating because of periods of wilting and just before the end of July (period 12), the cover decreased rapidly, falling to about 10% in period 13. In period 13, the cover on the irrigated plots started a slow decrease; this decrease in cover was greatly accelerated in period 14, falling to 10% on 28 August. On this date the unirrigated plants were almost leafless, a state reached by the irrigated plots a week later (4 September). Harvest was on 9 September.

Supplementary information is that the soil, except possibly in the surface layer, was as wet as it could be on 6 May, the time of the first monitoring. Subsequent soil moisture losses may therefore be interpreted as soil moisture defects directly. The inference of Table 3(I)A is that the transpiration check on the unirrigated crop over periods 6, 7 and 8 began at a deficit of 55–60 mm, that is about the time the freely available water in the top 30 cm was exhausted.

Up to period 6, (around 50% ground cover) the average rate of water extraction was around 0.8E_T. Over the main growing season for the crop free from soil moisture stress, a mean rate of water extraction was around 1,15E_T. Under a soil moisture stress, the rate of water extraction over the main part of the growing season was around 0.7E_T. This figure includes the removal of current rainfall.

2. For 1968, the basic information provided by Rothamsted is shown in Table 8 (II).

Table 8 (II)

Beans, 1968. Possible water balance and evaporation (mm)

	Period	R	Unirrigated site			Irrigated site		Accumulated
			D_o	E_o	I	D_I	E_I	E_T
1	21/5–31/5	5.3	19.9	25	–	19.6	25	25
2	31/5–6/6	8.4	6.6	15	–	10.9	19	40
3	6/6–12/6	2.8	20.4	23	23.5	– 0.2	26	60
4	12/6–19/6	2.0	18.3	20	–	24.0	26	85
5	19/6–26/6	19.0)	3.8	38	22.5	– 31	11	104
6	26/6–4/7	22.4)				10	32	128
7	4/7–18/7	79.5	– 53?	27?	26.5	– 67	39?	164
8	18/7–29/7	4.1	29?	33?	–	26	30?	188
9	29/7–27/8	60.8)	– 28?	58?	26.9	– 35	78?	259
10	27/8–5/9	25.4)						

The supplementary information set out in Table 8 (II) A may be inferred.

Table 8 (II)A

Beans, 1968. Possible water balance and evaporation (mm)

Period	D_o	Accumulated D_o	E_o	E_T	E_o/E_T	D_I	Accumulated D_I	E_I	E_I/E_T
1	19.9	19.9	25	25	1.00	19.6	19.6	25	1.00
2	6.6	26.5	15	15	1.00	10.9	30.5	19	1.27
3	20.4	46.9	23	20	1.15	– 0.2	30.3	26	1.30
4	18.3	65.2	20	25	0.80	24.0	54.3	26	1.04
5	– 3.8	61.4	38	43	0.88	– 31.	23.3	11	1.0
6						10	33.3	32	
7	– 53?	8.4	27	36	.75	– 67	0	39	1.08
8	29?	37.4	33	24	1.38	26	26	30	1.25
9	– 28?	19.4	58	71	0.82	– 35	0	78	1.10
10									

Ignoring some of the instrumental difficulties due to exterior flooding of the probe access tube, we may find some confirmation of the points brought out from the 1970 data eg

(i) a transpiration check on the unirrigated plot takes place between periods 3 and 4. The net drying measured up to the end of period 3 was 47mm. The absolute soil moisture deficit could be expected to be of the order 50+ mm.

(ii) Under soil moisture stress, that rate of water extraction is of the order $0.8E_T$ (including some rainfall removal).

(iii) For the unstressed, irrigated crop a mean value of the ratio E/E_T is around 1.1.

At the time of the first monitoring on 21 May, the plants were 20 cm high, giving about 20% cover. Growth thereafter was uniform, and a maximum height of 130-135 cm was teached about 10 July (period 7), with 100% cover. By the end of July, the pods were maturing and the lowest leaves in the plant were dying.

The initial rate of water extraction (before 50% cover) was estimated to be equal to E_T.

3. For the 1965 season at Rothamsted, the only information to be obtained relevant to a general model of behaviour is that the ratio E/E_T in this wet season was around 0.9. The measurements took place over the period from 3 June to 7 September. The inclusion of the senescent phase of the crop might be expected to lead to a ratio E/E_T less than 1.0.

4. From the 1966 season results at Rothamsted, confirmation is provided in the rooting depth; the unirrigated crop took most of the water from the top 90 cm of soil, the irrigated crop tapped little more than the top 60 cm.

Over periods with no excess rain, mean values for the ratio E/E_T were of the order 1.09-1.16.

5. The 1967 crop was drilled on 20 March and at the time of the first monitoring, on 16 May, was 10 cm tall. In the next 3 weeks there was excessive rain, with drainage. On 9 June, the first date on which tabulated data is made available, the crop was 45 cm tall with 55% cover. Crop height increased to 150 cm by early August, with 100% cover that then fell away to about 50% by early September.

Over the period 9 June to 10 August the ratios E/E_T for irrigated and unirrigated crops were respectively 1.11 and 0.93. Over the next period up 22 September, the corresponding figures were 0.6 and 0.5 respectively.

Graphed data are available over more frequent intervals than the 2 periods 9 June-10 August and 10 August to 22 September. There is evidence of a significant transpiration check in the first of these periods on the unirrigated crop.

6. The evidence of the 1971 season is that soil water depletion occurred primarily in the top 60 cm soil layer.

A transpiration check was apparent by the time a net drying of some 50 mm had been attained in the top 30 cm layer.

Average maximum drying in the top 30 cm of soil was around 55 mm; that in the next 30 cm of soil was perhaps 20 mm.

Typical values of the ratio E/E_T for the irrigated crop were 1.2. During the period of transpiration check for the unirrigated crop, smoothed (accumulated) values of the ratio E/E_T were close to 1.0, though, over short periods a ratio $E/E_T = 0.8$ could be established.

7. The suggested mode of water usage for field beans is as follows:

7.1 The soil reserves at field capacity available to field beans on the three broad soil types are taken to be

Layer	Heavy Soil	Medium Soil	Light Soil
0–30 cm	60 mm	45	30
30–60	35	25	20
60–90	10	10	10

7.2 During April, the land may lose water at the potential rate E_T, until a deficit of the order 25 mm is established. At this point there will be a transpiration check and any further moisture loss will be at a nominal rate equal to $0.1E_T$.

7.3 During May, the land may lose water at the potential transpiration rate E_T, until a deficit of the order 25 mm is established. At this point there will be a transpiration check, and any further water is lost at a rate equal to $0.5\ E_T$.

7.4 During June, July and the first half of August, the soil reserves in the top 30 cm of soil may be removed at a rate equal to $1.15\ E_T$. When these reserves are exhausted, there is a transpiration check and soil reserves in the 30–60 cm layer may be removed at a rate equal to $0.5E_T$. When the reserves in the 0–60 cm layer are exhausted, the remaining soil reserves in the 0–90 cm rooting zone may be removed at a rate equal to $0.3E_T$.

7.5 During the second half of August, and in September, soil moisture reserves in the 0–30 cm layer may be drawn on at a rate equal to $0.6E_T$. Should these reserves become exhausted, the reserves available in the 30–60cm layer may be extracted at a rate equal to $0.3E_T$.

7.6 In any period for which a moisture balance is being struck, current rainfall will be removed preferentially (at a rate equal to E_T, $1.15E_T$ or $0.6\ E_T$, ie at the maximum rate appropriate to the phase of growth indicated by month) before soil moisture reserves are modified in any way.

Meteorological Office
Cambridge
November 1973